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A review for the applications of solar chimneys in buildings

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ABSTRACT

As a simple and practical bioclimatic design methodology, solar chimneys are receiving considerable attention for reducing heat gain and inducing natural cooling or heating in both commercial and residential buildings because of their potential benefits in terms of operational cost, energy requirement and carbon dioxide emission. In practical civil buildings, solar chimneys can be installed on the walls and roofs. For the purpose of improving natural ventilation performance and achieving better indoor thermal comfort, solar chimneys are always applied in the form of integrated configurations. Solar chimneys can also be used to combine with natural cooling systems so as to enhance the cooling effect inside buildings. Besides, active solar systems may be utilized to enhance the ventilation performance of solar chimneys. In this paper, the main configurations and the integrated renewable energy systems based on solar chimneys were summarized. Then the suggestions were given. Generally, solar chimney technology has been regarded as an effective and economical design method in low carbon buildings. As for the integrated energy systems based upon solar chimneys, it is still necessary to carry out more experimental investigations to acquire objective data for the system design. Besides, it is suggested to further study the optimization and control strategy of such integrated systems in different climates.

Contents

1. Introduction

Buildings, energy and the environment are key issues facing the building professions worldwide [1]. Bioclimatic design of buildings is one strategy for sustainable development, as it contributes to reducing energy consumption and therefore ultimately, air pollution and greenhouse gas emissions from conventional energy generation. Bioclimatic design involves the application of energy conservation techniques in building construction, and the use of renewable energy such as solar energy and the utilization of clean fossil fuel technologies [2].

Being a simple and practical idea, the technology of solar chimney has been regarded as an attractive bioclimatic design. Solar chimney is a thermo-syphoning air channel in which the principal driving mechanism of air flow is through thermal buoyancy. It utilizes solar radiation to enhance the natural ventilation in buildings, which is achieved as a result of the fact that the solar energy causes a temperature rise as well as a density drop in the air inside the solar chimney. The drop in air density causes air within the solar chimney to rise and be expelled out of the top of the chimney [3].

A solar chimney could be vertical or inclined. Different configurations for solar chimney in buildings have been proposed, which

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could be grouped into two families: wall solar collector (solar wall or Trombe wall) and roof solar collector. The structural feature is typically composed of an absorber wall, an air gap and a glass cover with high solar transmissivity and is designed to maximize solar gain in order to increase the chimney effect and thus the air flow generated by the chimney. However, in some cases, the glass cover may be integrated with photovoltaic cells or substituted by an opaque cover.

Some model experiments and theoretical investigations have been carried out to study the effects of geometry, inclination angle and meteorological parameters on the ventilation performance of solar chimneys. Afonso and Oliveira [4] compared the behavior of a solar chimney with a conventional one. The experimental results showed that there was a significant increase in ventilation rate with the solar chimney. Chen et al. [5] studied the solar chimneys with a uniform heat flux on a single wall for different chimney gaps, heat flux input and different chimney inclinations. It was found that a maximum airflow rate was achieved at an inclination angle around 45° for a 200 mm gap and 1.5 m high chimney. Zhai et al. [6] carried out another similar experiment regarding to a solar chimney, for which the length of air channel was 1500 mm, the width was 500 mm, and a variable air channel gap ranged from 100 to 500 mm. In the experiment, the uniform heat flux along the air channel was generated by three electric heating plates, which played a role as solar radiation. It was observed that the temperature distribution of air and the induced natural air flow rate were highly dependent on heat input, inclination angle, channel gap, etc. The experimental results indicated that the optimum inclination angle for the solar chimney was 45°, under which a maximum natural ventilation rate could be created. Also found was that there existed an appropriate channel length, about 1 m in this study, beyond which the natural ventilation rate could not be increased drastically. Ziskind et al. [7] designed an experimental set-up to simulate a one-story building, with a part of its roof exposed to solar irradiation. A heating plate was used to serve as solar irradiation. It was the bottom of a tin tank in which the boiling of water was achieved by immersion of two electrical heaters, thus providing constant temperature of the plate. The experimental results proved that effective ventilation could be achieved by means of natural convection heat transfer from a hot element of the building, heated by solar radiation. The performance of several designs of the hot element and ports of the building were analyzed. It was observed that the exit port should be located near the ceiling in order to obtain uniform temperature distribution inside the building. Mathur et al. [8] carried out experimental investigations on a small size solar chimney. Nine different combinations of absorber height and air gap were studied on the experimental set-up. It was indicated that the rate of ventilation increased with increase of the ratio between height of absorber and gap between glass and absorber. The highest rate of ventilation induced with the help of solar energy was found to be 5.6 air change per hour in a room of 27 m^3, at solar radiation of 700 W/m^2 on vertical surface with the stack height-air gap ratio of 2.83 for a 1 m high chimney.

As for theoretical investigations, the mathematical model of a solar chimney can be set up based upon steady state heat transfer equations. Ong [9] made use of this mathematical technique to determine the boundary temperatures at the surface of the glass cover, the rear solar heat absorbing wall and the air flow in the channel by means of a thermal resistance network. Balocco [10] developed a similar model to analyse the energy performance of a ventilated facade. The simulated results showed that it was possible to obtain a sensible solar cooling effect during summer, when the air cavity width of the chimney was wider than 7 cm. For wider cavities the cooling effect became stable. This model was reported to be useful to understand the heat transfer mechanism and then the energy performances of ventilated facades. Afonso and Oliveira [4] developed a simplified model and a computer program that allowed the quantification of solar assisted natural ventilation flow rate. They took into account the time variation in climatic conditions, as well as the heat storage in the chimney walls. It was concluded that there was a significant increase in ventilation rate with solar chimneys, and that the thermal model predicted with good accuracy the measurements carried out. Bassiouny and Korah [11] studied the effect of chimney inclination angle on the air change per hour and indoor flow pattern. The analytical results demonstrated that an optimum air flow rate value was achieved when the chimney inclination was between 45° and 70° for latitude of 28.4°. Moreover, a correlation to predict the air change per hour was developed. The correlation was tested within a solar intensity greater than or equal to 500 W/m^2, and chimney width from 0.1 m to 0.35 m for different inclination angles with acceptable values. It was concluded that the chimney inclination angle was an important parameter that greatly affected the space flow pattern and ventilation rate.

The numerical modelling of solar chimneys using computational fluid dynamics (CFD) technique has attracted increasing attention. Gan [12] developed a CFD program for the prediction of buoyant air flow and flow rate in enclosures with Trombe wall geometries. It was found that, when a Trombe wall was used for summer cooling, the ventilation rate induced by the buoyancy effect increased with the wall temperature, solar heat gain, wall height and thickness. The use of double glazing instead of single glazing for a Trombe wall system not only reduced heat losses in winter but also enhanced passive cooling in summer. To maximize the ventilation rate for summer cooling, the interior surface of the storage wall should be insulated. This also prevented undesirable overheating of room air due to convection and radiation heat transfer from the wall. Gan [13] used the CFD technique to investigate the performance of a glazed solar chimney for heat recovery in naturally ventilated buildings. It was shown that installing heat pipes in the chimney for heat recovery not only increased the flow resistance but also decreased the thermal buoyancy effect. To achieve the required air flow rates in naturally ventilated buildings with heat recovery, use should be made of wind forces. Moshfegh and Sandberg [14] analyzed the flow and heat transfer characteristics of buoyancy-driven air convection behind photovoltaic panels. Both convection and radiation heat exchanges were considered as the heat transfer mechanisms by which the thermal energy was transferred into the air. The numerical and experimental results were obtained for a channel of 7.0 m in height and the channel walls were separated by a distance of 0.23 m. In the experiment, the heat was supplied to the air gap from the heating foil attached to one of the vertical walls. Different input heat fluxes and emissivity of the bounding surfaces were considered in order to show their effect on the heat transfer across the air layer. Detailed studies of the flow and thermal fields in the air were presented in order to explore the thermal behavior of the air in the channel. The velocity and temperature profiles of the outlet air and the surface temperature of the heated and insulated wall were presented. The numerical results agreed well with the experimental measurements. Rodrigues et al. [15] utilized the conservation equations of motion and energy, along with a two-equation k–ε turbulence model to describe the turbulent natural convection in a two-dimensional vertical channel with asymmetric heating on walls. The flow and temperature fields were produced. Besides, the results were presented in terms of temperature and velocity distributions at the exit section of the duct. These enabled a better understanding of the developing flow and could be helpful in the design phase of this type of system. Gan [16] presented the results of CFD simulation of the buoyancy-driven airflow and heat transfer in vertical cavities of different heights and widths with different total heat fluxes and wall heat distributions for ventilation cooling. Two sizes of computational domain were used for simulation – a small domain same as the physical size of a cavity

and a large extended domain that was much larger than the cavity. The predicted natural ventilation rate and heat transfer coefficient were found to depend on not only the cavity size and the quantity and proportion of heat distribution on the cavity walls but also the domain size. The difference in the predicted ventilation rate or heat transfer coefficient using the small and large domains was generally larger for wider cavities where heat distribution on two vertical walls was highly asymmetrical; incoming air would be distorted from symmetrical distribution across the inlet opening; and/or significant reverse flow would occur at the outlet opening. The difference in the heat transfer coefficient was generally less than that in the ventilation rate. In addition, a cavity with symmetrical heating had a higher ventilation rate but lower heat transfer coefficient than did an asymmetrically heated cavity.

Besides, Lee and Strand [3] described the basic concepts, assumptions, and algorithms implemented into the EnergyPlus program to predict the performance of a solar chimney. The effects of the chimney height, solar absorptance of the absorber wall, solar transmittance of the glass cover and the air gap width were investigated under various conditions. The chimney height, solar absorptance and solar transmittance turned out to have more influence on the ventilation enhancement than the air gap width. The potential energy impacts of a solar chimney under three different climate conditions were also investigated. It was indicated that significant building cooling energy saving could be achieved by properly employing solar chimneys and that they had more potential for cooling than for heating. In addition, the performance of a solar chimney was heavily dependent on the climate of the location.

According to the above-mentioned reports, it is deduced that the shape and physical properties of the channel as well as the operating conditions influence greatly the performance of the solar chimney. Besides, it is testified that solar chimneys are capable of enhancing natural ventilation, and thus have the potential of energy conservation in buildings.

The solar chimney concept has been applied to both commercial and residential buildings for several decades to reduce heat transfer through the walls and roofs, thus easing the cooling load of air-conditioning systems. Solar chimneys also induce natural ventilation. As a consequence, a substitution of fresh air is induced into the houses, which participates to improve the indoor thermal comfort. By far the most popular application is the well known Trombe wall composed of a glass cover, an air gap and a concrete wall. Since, the idea of passive ventilation based on solar heating has gained growing interest and various design configurations have been proposed worldwide [17,18].

Solar chimneys can be used independently in buildings. However, for the purpose of improving natural ventilation effect, solar chimneys are always integrated with other technologies. It is believed that such integrated design approaches can induce higher air flow rate and maintain more comfortable indoor thermal environment. In this paper, the main integrated configurations of solar chimneys with buildings were introduced. And then, the integrated renewable energy systems based upon solar chimneys were summarized. Finally, some suggestions on the design of solar chimney systems were given.

2. Applications of solar chimneys in buildings

2.1. Applications of solar chimneys based on roofs of buildings

The buildings with gable roofs can be well designed for integration with solar chimneys to form the roof solar collectors. In summer, it is feasible to use the roof structure to induce natural air circulation, which is a part of the indoor thermal comfort of buildings. Khedari et al. [19] discussed the possibility of offering thermal comfort in new houses built in European style and situated in a hot and humid climate, without inducing mechanical energy cost, by means of a roof solar collector. With this roof solar collector it was possible, on one hand, to minimize the fraction of the solar flux absorbed by the dwelling and, on the other hand, to induce natural ventilation which improved its thermal comfort. The influence of length and tilt angle of the roof solar collector and local constructing materials used on the performance of the roof solar collector was studied experimentally. It was shown that the appropriate materials of the roof solar collector, with regard to the improved natural ventilation, should be CPAC (Concrete Product and Aggregate Company Ltd.) Monier concrete tiles on the outer side and gypsum board on the inner one. The optimum dimensions were suggested as the following: short length about 100 cm; tilt at 30°; and the space plates equal to 14 cm. The rates of natural air ventilation and energy evacuated by the roof solar collector were about 0.08–0.15 $m^3/s\,m^2$, and 150–350 W/m^2, respectively.

Whereafter, Khedari et al. [20] tested the performance of two units of roof solar collector which were integrated in the roof structure of a school solar house. The effects of air gap and openings of the roof solar collector on the induced air flow rate and thermal comfort were studied. The experimental results showed that large air gap and large and equal size of openings would induce the highest rate of air flow rate. In addition, as extra cost of the construction according to the proposed configuration would not increase very significantly; the designers and architects were suggested to consider these propositions in their further designs.

Based upon the numerical results, Hirunlabh et al. [21] found that the air flow rate per unit area of the roof solar collector decreased with the increase of length of the roof solar collector. Thus, the amount of air flow rate induced by one longer roof solar collector would be lower than that induced by two units of the roof solar collector, with a total length equal to that of the longer unit. Therefore, to maximize the air ventilation by the roof solar collector systems, the length of the roof solar collector should be shorter, in the order of 100–200 cm. On the basis of this conclusion, they proposed four different configurations of the roof solar collector to maximize natural ventilation, as shown in Fig. 1.

The majority of the current researches on roof solar collectors were concerned with natural ventilation. However, space heating in winter is as necessary as ventilation in summer for most regions. Zhai et al. [22] proposed two kinds of roof solar collectors, namely, the single pass roof solar collector, and the double pass roof solar collector. To evaluate the effects of two roof solar collectors for both space heating and natural ventilation, a single traditional Chinese style house, on which the two roof solar collectors would be mounted respectively, was developed.

The configuration of single pass roof solar collector, which is formed by integrating single pass solar air collector with southern roof of the building, is shown in Fig. 2. By switching damper 1 and 2, the roof solar collector can be used to implement two operating modes, namely, space heating in winter and natural ventilation in other seasons. In winter, space heating is needed. The indoor air can be circulated between the inner house and the roof solar collector by closing damper 1 and opening damper 2. In this case, a fan is used to move the air. Natural ventilation, which is necessary for other seasons, can be effected by closing damper 2 and opening damper 1. Thus the indoor air can enter the air channel through tuyere 7 under the chimney effect caused by solar radiation. The air is then exhausted to the ambient.

The double pass roof solar collector, which is configured by integrating a double pass solar air collector with the southern roof of the building, is presented in Fig. 3. Some changes are made to rebuild the double pass roof solar collector, as is shown in Fig. 3, four additional dampers 1, 2, 3, and 7 are installed to the switch operating modes between space heating by warm air in winter and

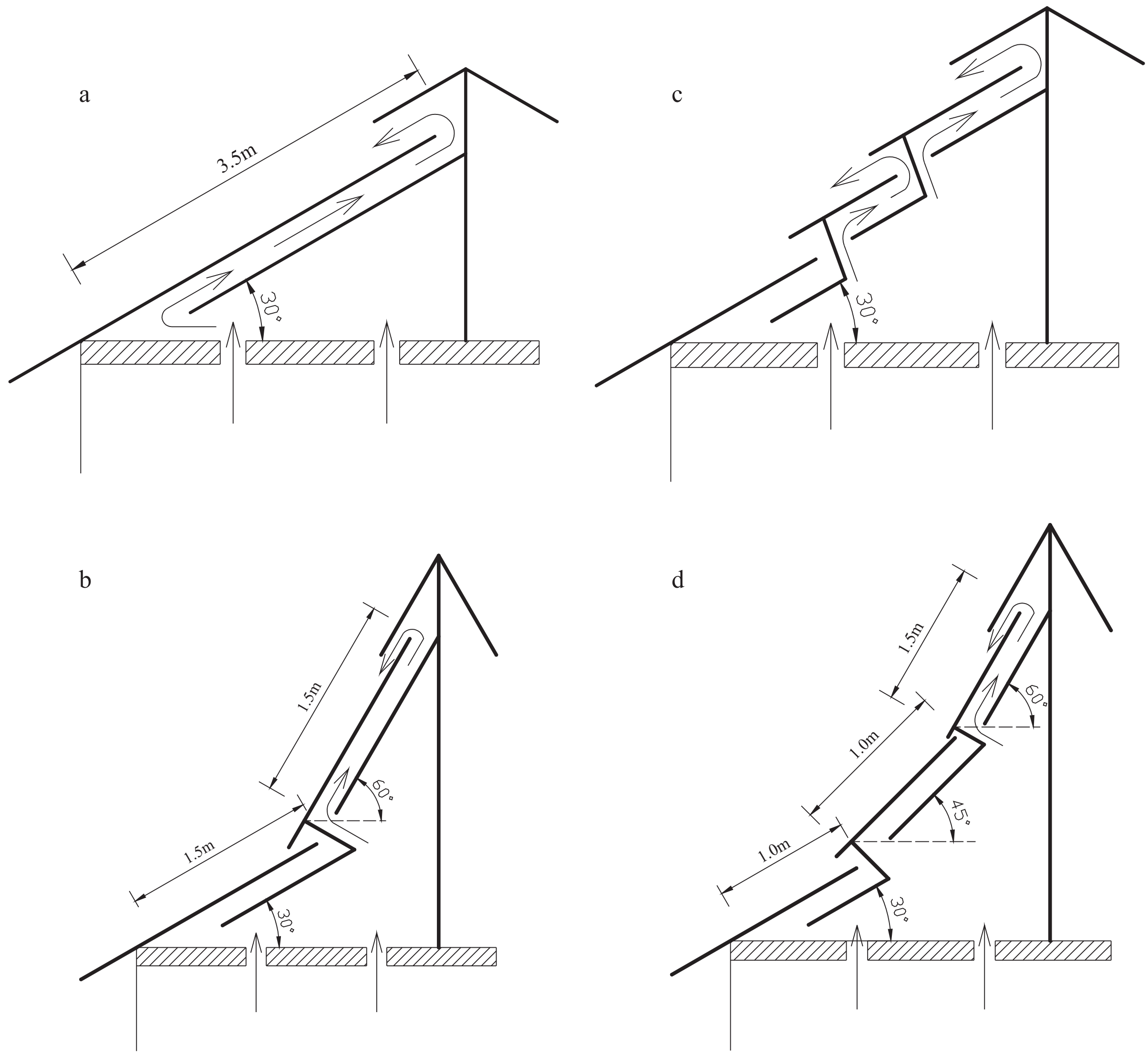


Fig. 1. Four different configurations of the roof solar collector [21].

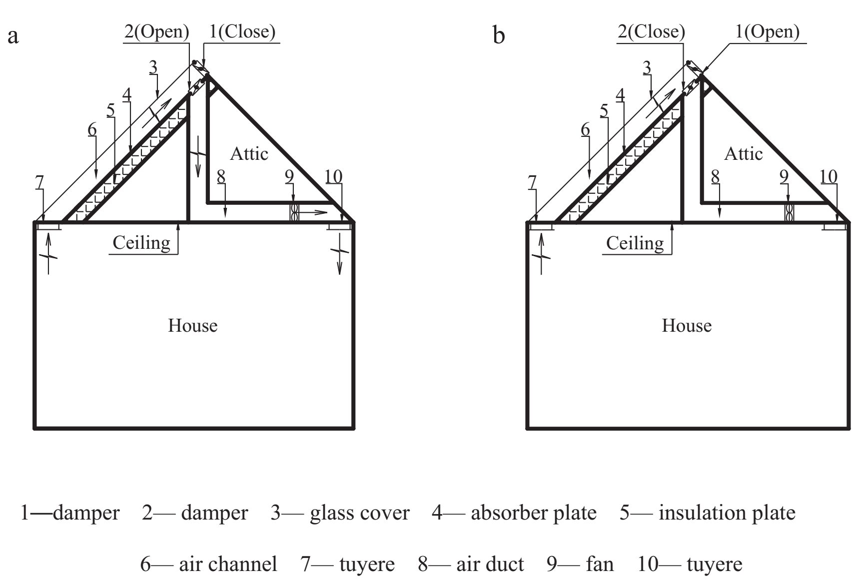


Fig. 2. Structure of single pass roof solar collector. (a) Space heating mode. (b) Natural ventilation mode [22].

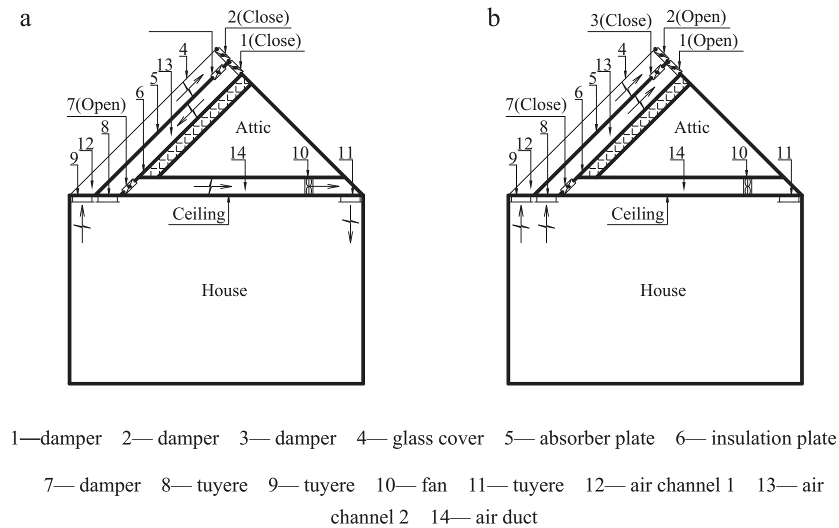


Fig. 3. Structure of double pass roof solar collector. (a) Space heating mode. (b) Natural ventilation mode [22].

natural ventilation in other seasons. Space heating is operated with the following procedures: (1) closing dampers 1 and 2, (2) opening dampers 3 and 7, (3) closing tuyere 8. In this way, the indoor air can enter air channel 1 through tuyere 9 and get heat from solar radiation. Then the air flows into air channel 2, where the absorber plate secondly heats the air; thereafter it flows into air duct, and is supplied into the house by the fan through tuyere 11. Natural ventilation mode is accomplished by closing dampers 3 and 7, and opening dampers 1 and 2. Thus the indoor air can enter both air channel 1 and 2 through tuyeres 8 and 9, respectively. In the air channels, the air is heated by solar radiation and the natural ventilation can thus be produced in the end due to the chimney effect.

Through comparison, it was found that the instantaneous efficiency of solar heat collecting for the double pass roof solar collector was higher than that of the single pass one by 10% on average, and natural ventilation air mass flow rate contributed by natural ventilation for the double pass roof solar collector could be improved to a great extent for most cases, indicating that the double pass roof solar collector was superior to the single pass one from the points of view of both space heating and natural ventilation. The double pass roof solar collector was therefore more potential for improving indoor thermal environment and energy saving of buildings.

2.2. Applications of solar chimneys based on walls of buildings

A wall solar collector (solar wall or Trombe wall) is a vertical channel attached to the exterior wall of a building. Solar radiation warms up the surface, and upward selfdriven flows are triggered by the temperature differences between the collector and the ambient. This air stream can be used for ventilation and heating of buildings [23]. Bansal [24] depicted a wall solar collector used in high mountain regions in the North and North-Eastern Himalayas for space heating during the winter periods. It was found that the wall solar collector worked with an overall efficiency of 32.5% and it was able to collect 2.3 kWh/m^2 of energy per day on an average basis.

The standard Trombe wall has two main drawbacks. During cold and cloudy winter days, it causes important heat losses and thus discomfort to the occupants. In summer, it creates important and undesired inputs. These drawbacks can be eliminated by a more complex design such as the composite Trombe wall [25]. Zalewski et al. [25] designed a massive solar wall, with an insulating panel located just behind it. A ventilated air layer existed between this panel and the wall. The vents located at the top and the bottom of the insulating panel allowed air circulation and thus energy inputs to the building. A prototype was built into a test room. The experimental results demonstrated that such type of solar wall was superior to the traditional Trombe wall.

Due to their large surface area per unit of volume, porous materials can be used as channel thermal enhancers. Boutin and Gosselin [23] described the behavior of a vertical open-ended wall filled with a porous matrix. It was reported that the porous structures in thermal systems such as solar wall and solar chimney could play an important role for improving energy efficiency.

Hirunlabh et al. [26] reported the natural ventilation performance of a metallic solar wall. The metallic solar wall consisted of a glass cover, air gap, black metallic plate and insulator made of micro-fiber and plywood. Fig. 4 shows the schematic representation of the passive solar house and the natural ventilation by the metallic solar wall. It was found that the metallic solar wall with 14.5 cm air gap and 2 m^2 of surface area produced the highest air mass flow rate of about 0.01–0.02 kg/s. The room temperature during the tests was near to ambient temperature, ensuring human comfort resulting from the ventilation produced by the metallic solar wall. The metallic solar wall could significantly reduce heat gain in the house by developing air circulation to improve the thermal comfort. It was said that the proposed system was economical due to little cost of materials used. Also such a passive use of solar energy was energy efficient.

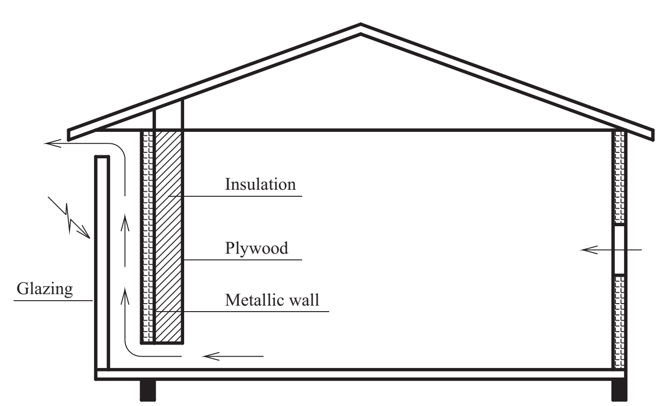


Fig. 4. Schematic representation of the passive solar house and natural ventilation by metallic solar wall [26].

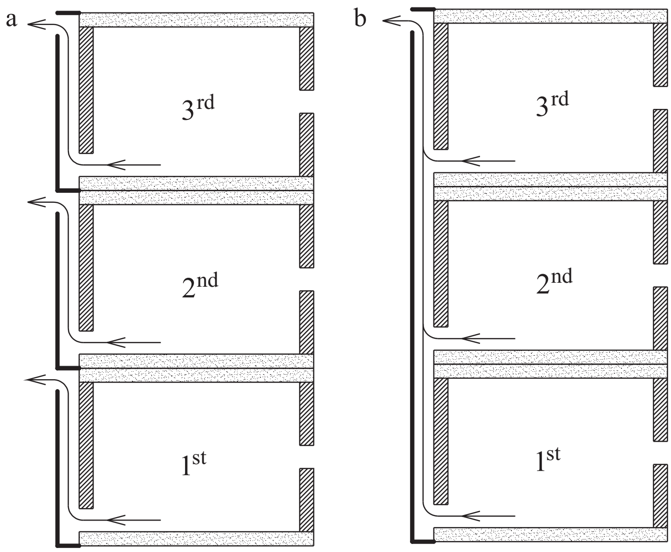


Fig. 5. Multi-solar chimney configurations. (a) Separated solar chimney. (b) Combined solar chimney [18].



Fig. 6. West facade with solar chimneys of the building [28].

Punyasompun et al. [18] conducted an experimental and numerical study of the high-rise solar chimney building under Bangkok climatic conditions. Two small scale models of a three storey building were built. The solar chimneys were integrated into the south-faced walls of one unit whereas the other unit served as a reference. Two design configurations were considered including the connected and nonconnected solar chimney, as is shown in Fig. 5. The former was a tall solar chimney with an inlet opening at each floor and one outlet opening at the third floor (combined solar chimney). While for the latter, an inlet and outlet openings were installed at each floor (separated solar chimney). The comparison between the solar chimney model and common model demonstrated that the multi-storey solar chimney was a good alternative and could be applied effectively. The room temperature of the solar chimney model was lower than that of the other model by about 4–5 °C. The next comparison between the two solar chimney configurations showed that the recommended configuration was the combined solar chimney with an inlet opening at each floor and one outlet opening at the third floor. Therefore multi-storey solar chimney was believed to be an interesting option and could be applied for hot climate like Thailand to save energy and environment.

Altan et al. [27] reported the passive solar design strategy of a green building. The glazed southern facade of this building faced to a buffer zone with the stack natural ventilation service. Solar radiation transmitted through the glazed facade heated the air which then rose and was vented out at the top, and the replacement air was supplied via openings on the north facade which provided cross ventilation across the building. Therefore, the passive cooling could be driven. The initial findings of an internal assessment of the thermal comfort indicated that such designs were to be commended for their passive use of solar energy and could provide a high quality working environment.

Macias et al. [28] presented a passive night cooling system which was developed and implemented for a new project of social housing. The passive cooling system incorporated a solar chimney in combination with high thermal mass in the building construction. The natural ventilation was enhanced with the help of the solar chimney and night fresh air cooled the building structure. Fig. 6 shows the west facade with solar chimneys of the building. These chimneys, oriented to the west, collected solar gains during the afternoon in their concrete walls, reaching temperatures up to 50 °C. While they were collecting, the chimneys were closed. During the night when the ambient temperatures were down to around 20 °C, the flaps at the top of the chimneys were opened and the chimney effect of the collected heat sucked the exhaust air out of the apartments. The fresh cold night air entered through the east facade and ran through the flat, cooling down the thermal-masses of the walls and ceilings. To comply with fire regulations, every flat had its own chimney, without a connection to the other flats. This type of solar chimney allowed a totally passive night time cross-ventilation without having to open the window. They were accepted because, solving a very typical conflict between noise and ventilation, they would represent a considerable contribution to the bioclimatic field in an urban context.

2.3. Integrated configurations based on solar chimneys

With only a solar chimney system, there is little potential in inducing sufficient natural ventilation to satisfy indoor thermal comfort. However, the integrated configurations which combine one solar chimney with another solar chimney wall or roof configurations can induce higher air ventilation rate, allowing the substitution of stagnant room air with fresh outside air for a healthy and comfortable interior environment and maintain indoor temperature at comfortable level [18].

Mohammad Yusoff et al. [29] proposed a solar induced ventilation strategy which consisted of two parts, namely a roof solar collector and a vertical stack. The purpose of the roof solar collector was to capture as much solar radiation as possible, thus maximizing the air temperature inside the channel of the roof solar collector. The heated air inside the channel rose and flowed into the vertical stack due to the pressure difference between the two zones. Meanwhile, the vertical stack was important in providing significant height for sufficient stack pressure. The walls of vertical stack were insulated in minimizing the heat loss to the environment. The findings indicated that the proposed strategy was able to enhance the stack ventilation, both in semi-clear sky and overcast sky conditions. The highest air temperature difference between the air inside the stack and the ambient air was achieved in the semi-clear sky condition, which was about 9.9 °C (45.8–35.9 °C). Besides, in the overcast sky condition, the highest air temperature difference was 6.2 °C (39.3–33.1 °C). The proposed integrated configuration was reported to be able to create a higher air temperature difference than the usual air temperature difference attained by Malaysia naturally ventilated buildings.

AboulNaga and Abdrabboh [30] presented the theoretical investigation of a combined wall-roof solar chimney to improve night

ventilation in buildings. A spreadsheet computer program was used for the parametric study to find out the optimum configuration of the wall-roof chimney. The analysis showed that it was possible to create a maximum air flow rate of 2.3 m^3/s. To obtain such an air flow rate the wall should be extended to 3.45 m high with an inlet height of 0.15 m, and a total height of 3.60 m. The length of the wall less than 3.00 m would decrease the induced air flow rate. The incorporation of a combined wall-roof solar chimney to a single house in Al-Ain, a hot-arid climate region, induced an air change per hour up to 26. The parametric study yielded an increase in the induced air flow rate as a result of combining the wall-roof chimney three times greater than that of the roof solar chimney alone. Such a design approach could be utilized to improve night ventilation to reduce indoor air temperature and cool low-rise heavy buildings with large diurnal outdoor temperature variations.

2.4. Integrated renewable energy systems based on solar chimneys

2.4.1. Integration of natural cooling systems with solar chimneys

Due to the internal gains and heat transmission through the wall and roof, daytime ventilation is usually required to improve the indoor air quality and to remove the heat. The outdoor air can be induced into buildings by solar chimneys. However, if the outdoor air temperature exceeds the thermal comfort limit, it is necessary to precool it. The precooling of external air before entering the building can be achieved by natural means, such as evaporative cooling, ground cooling, etc. Macias et al. [31] reported a passive cooling system which was developed as a part of design work for the project of a low cost residential building. The passive cooling system incorporated a solar chimney and precooled the air by using the sanitary area of the building. The natural ventilation was enhanced with the help of the solar chimney and fresh air was cooled down by circulation within the sanitary area. The application of this system to the living rooms of the low cost residential building was evaluated and implemented. It was found that the implementation of the passive cooling strategy allowed ensuring thermal comfort through low conventional energy consumption. By applying this low cost concept to a building located in Madrid, Spain, it was possible to predict a low energy demand during operation. That reduction could be more than 50% if the strategies for winter and summer were combined.

Maerefat and Haghighi [32] presented a passive solar system comprising of solar chimneys and earth to air heat exchangers. A schematic plan of the passively cooled room is shown in Fig. 7. This system realized both cooling and ventilation during daytime with the help of solar energy, thus it was natural day ventilating technique. The proposed solar system consisted of two parts: the solar chimney, and the earth to air heat exchanger. The solar chimney included a glass surface oriented to the south and an absorber wall that worked as a capturing surface. The air was heated up in the solar chimney by the solar energy, and flowed upward because of the stack effect. It caused driving force which sucked the outside air through the cooling pipe. The earth to air heat exchanger was composed of horizontal long pipes that were buried under the bare surface at the specific depth. The pipes were spread under the ground in a parallel manner. It was shown that the solar chimney could be perfectly used to power the underground cooling system during the daytime, without any need of electricity. Moreover, this system with a proper design might also provide a thermally comfortable indoor environment for a large number of hours in the scorching summer days. The results of the study on the diameter of earth to air heat exchanger showed that there was an optimum diameter for cooling pipes (0.5 m) which gave the minimum required number of solar chimneys and earth to air heat exchangers. Besides, the long earth to air heat exchanger with the length of more than 20 m should be employed to provide the thermal comfort condition. The results also showed that when the ambient temperature and cooling demand were high, although providing thermal comfort was difficult, proper configurations could provide good indoor condition even in the poor solar intensity of 100 W/m^2 and high ambient air temperature of 50 °C.

Calderaro and Agnoli [33] proposed to install solar chimneys close to high thermic storage structures in an energetic retrofit. By the integration of the indirect evaporation system, the simulation results showed that such a collector storage system was capable of softening summer temperatures. In winter, it allowed the contemporary working of thermal storage and heat transferring toward the bordered setting, through natural thermic circulation circuits. The energetic consumptions and the environmental pollution could thus be reduced.

Maerefat and Haghighi [34] put forward a new solar system employing a solar chimney together with an evaporative cooling cavity, as is shown in Fig. 8. The numerical experiments showed that this integrated system with proper configuration was capable of providing good indoor conditions at the daytime in a living room even at a poor solar intensity of 200 W/m^2 and high ambient air temperature of 40 °C. Although the performance strongly depended on the ambient air humidity; it was easy to prepare good indoor thermal conditions for ambient air relative humidity lower than 50% even at high ambient temperatures. As such, this technique was suitable to supply the cooling load in the moderate and arid climates. The ventilation rate was influenced by solar radiation, ambient temperature, as well as geometrical configurations of both the solar chimney and the evaporative cooling cavity. The numerical experiments also indicated that the use of solar chimney with variable inlet dimensions was a way to control the air change rate per hour and the air temperature of the room. It was suggested that a combination of the proposed system with a conventional air conditioning system would help to create a reasonable indoor environment for human thermal comfort as well as to be energy efficient and environmentally friendly.

Raman et al. [35] tested a passive solar house based on the incorporation of solar chimneys for heating, cooling and ventilation in composite climates. The air handling capacity of solar chimneys was predicted by computation and verified by measurements. The passive model 1 (as shown in Fig. 9) consisting of a set of two solar chimneys, an evaporative cooler (for summer) and added wall insulation, performed well for winter, but the summer cooling was not adequate. Consequently, a second passive model 2 (as shown in Fig. 10), which consisted of a south wall collection and a roof duct cooled from above by a sack cloth evaporative cooling system was constructed and monitored for one year. The thermal performance of passive model 2 was distinctly better than that of model 1. The room maintained a temperature of about 28 °C during summer and about 17 °C in winter, which could be considered as a very satisfactory performance for the composite climates. The additional cost of providing passive components and wall insulation was estimated to be about 20% of the cost of a conventional room. Judging from the increasing costs of electricity and deteriorating power situation, the proposed passive system seemed to have good potential.

Chungloo and Limmeechokchai [36] studied the benefits of application of solar chimney on the south roof and cool metal ceiling on the north roof through the experiment in a detached building. The mean cooling potential of the application of combined system was found to be two times higher than that of the solar chimney alone. The application of cool ceiling and solar chimney, which reduced the ceiling temperature by 2–4 °C, did not only increase the circulation in the upper and lower regions of the room but also reduce the air temperature in the room by 0.5–0.7 °C, which could increase the comfort opportunity. The benefit of cool ceiling was also recognized by the increase of volume flow rate of air in

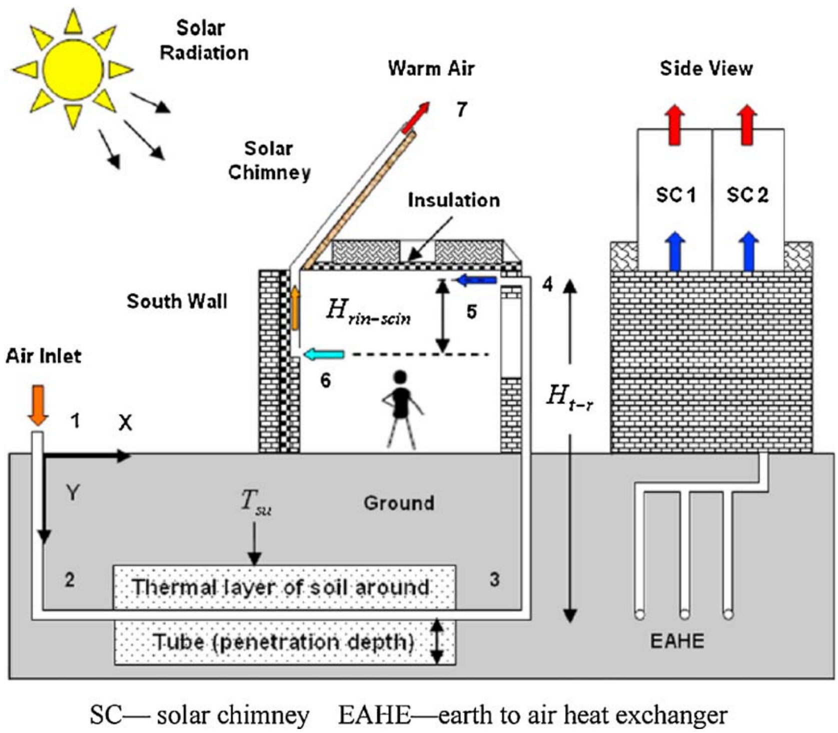


Fig. 7. Schematic diagram of integrated earth to air heat exchanger and solar chimney [32].

the application of cool ceiling comparing to the decrease of volume flow rate of air in the application of precooled air to the room.

Dai et al. [37] presented a parametric analytical study on the enhancement of natural ventilation in a solar house induced by a solar chimney and a solid adsorption cooling cavity. Fig. 11 shows the schematic of the solar house with solar chimney and adsorption cooling cavity. Theoretical analyses were carried out to investigate the ventilation in the solar house with solar chimney alone, cooling cavity alone or with combined solar chimney and solar adsorption cooling cavity, without considering the wind effects. It was found that on a typical day, the solar house comprising of a 2.5 m^2 solar chimney, was able to create an air flow rate of more than 150 kg/h for the studied house. In addition, the ventilation rate at night was also increased by about 20% with the solar adsorption cooling cavity. Besides, a solar adsorption cooling could attain a value of 0.12 for COP, which not only increased ventilation, but also provided cooling to the room without any change in humidity. The proposed concept was expected to be useful to be incorporated with a stand-alone building or with a cluster of buildings for some favorable climates.

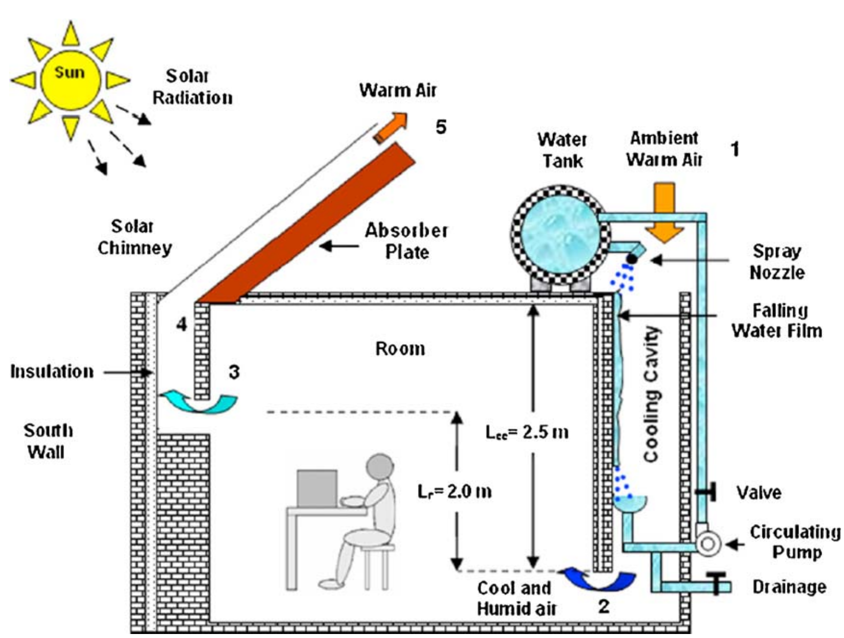


Fig. 8. Schematic diagram of solar chimney and cooling cavity [34].

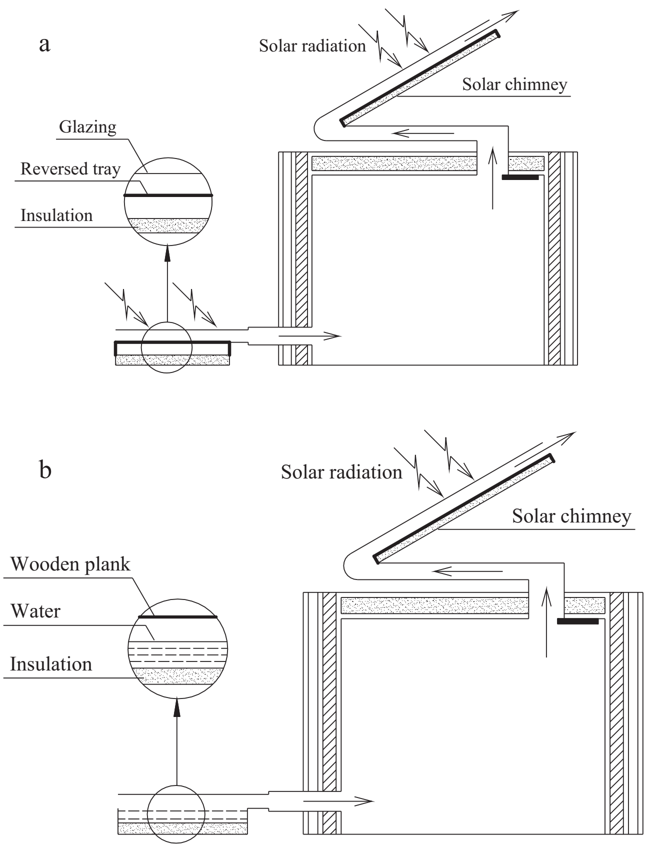


Fig. 9. Schematic diagram of passive model 1. (a) Operation in winter. (b) Operation in summer [35].

2.4.2. Integration of active solar systems with solar chimneys

Solar collectors can be used actively to enhance natural ventilation by stack effect, or photovoltaic generation technology can be used to acquire electricity fed to fans to promote ventilation, in these solar-enhanced ventilation technologies, the solar radiation will be transformed into the heat energy or the electrical energy at

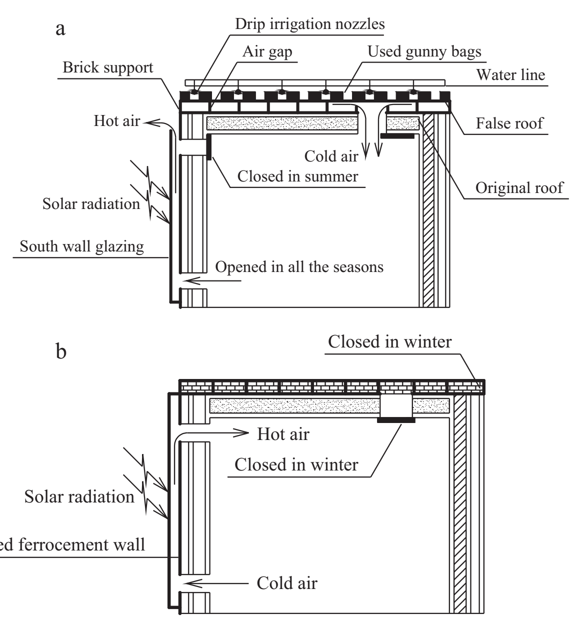


Fig. 10. Schematic diagram of passive model 2. (a) Operation in summer. (b) Operation in winter [35].

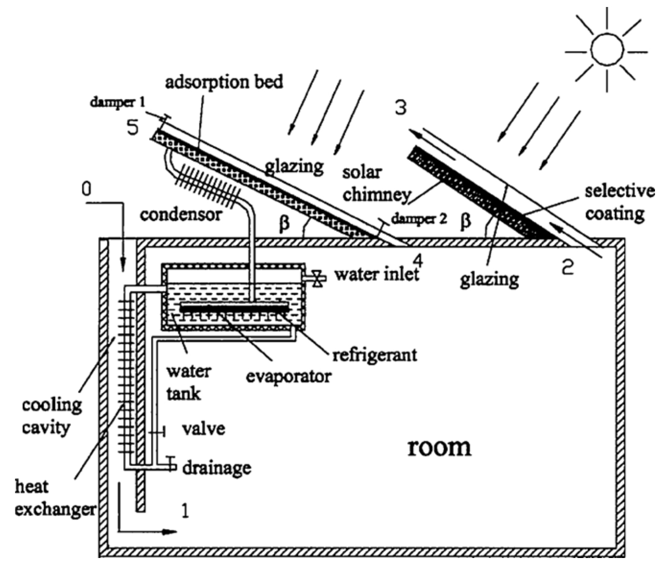


Fig. 11. Schematic of the solar house with solar chimney and adsorption cooling cavity [37].

the first step [38]. Khedari et al. [17] put forward a PV-powered roof solar collector system. A simple PV ventilation system was used to enhance the performance of roof solar collector for reducing heat gain and increasing the ventilation rate inside the house. The PV system consisted of one PV panel (27 Wp), a DC electrical fan (7.3 W) installed in the gap of roof solar collector and a control unit. The average PV powered air flow rate and the corresponding air change per unit roof solar collector were about 100–250 m^3/h and 3–8 ACH, respectively. Such rates were 2–4 times higher than those obtained with the natural ventilation induced by the roof solar collector. The proposed system led to a more comfortable indoor condition than those when the ventilation was induced by the roof solar chimney alone. Due to its simplicity (no battery was used), the proposed system was relatively cheap. Therefore, commercial application seemed to be viable. Another advantage of this system was that it promoted the use of photovoltaic panels. In addition, the PV-powered roof solar collectors could also be applied for air conditioned buildings as a means to reduce cooling load through the roof.

Zhai et al. [39] presented a novel design of natural ventilation enhanced by a solar hot water system. The 150 m^2 evacuated tubular solar collectors were installed on the roof of the green building of Shanghai institute of architecture science. For the purpose of efficient utilization of solar energy, the architects designed a steel structure roof, facing due south and tilted at an angle of 40° to the ground surface, on which the solar collectors were mounted and integrated with the building perfectly. The solar collectors were used to supply heating in winter and cooling in summer. However, in transition seasons, they were utilized to enhance natural ventilation and supply hot water.

There was an air channel under the roof of the green building, which was designed as a roof solar collector for the indoor air exhaust through natural ventilation. In order to enhance the natural ventilation by stack pressure, seven groups of heat exchange elements were installed inside the air channel. Each group consisted of three parallel finned tube heat exchangers as shown in Fig. 12. The finned tube heat exchanger was made of a 3-m-long copper tube with 540 square fins. The diameter of the tube was 20 mm and the sectional dimension of the square fins was 102 mm × 102 mm. In transitional seasons, the solar hot water was pumped into the finned tube heat exchangers to induce stack pressure, which was capable of improving natural ventilation. It was found that under

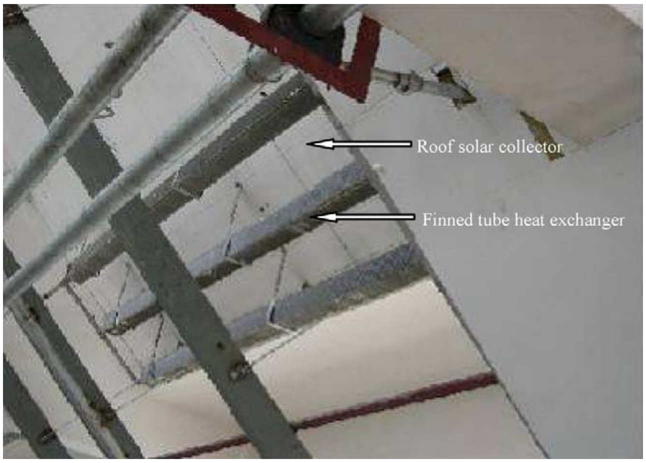


Fig. 12. Finned tube heat exchanger inside air channel [39].

typical working condition in transition seasons (daily solar insolation of 17 MJ/m^2 and average ambient temperature of 10 °C), the solar-enhanced natural ventilation air flow rate induced by stack pressure was doubled compared with conventional natural ventilation. Consequently, besides supplying hot water for the office building, the system was capable of inducing air change rate of 3 air change per hour.

3. Conclusions and suggestions

Solar chimneys are receiving considerable attention for reducing heat gain and inducing natural cooling or heating in both commercial and residential buildings because of their potential benefits in terms of operational cost, energy requirement and carbon dioxide emission. They can be widely utilized in the areas with adequate solar radiation. It has been testified that solar chimney technology is a very suitable system for regions where solar irradiation is high and wind speed is normally low [30]. Besides, in the hot and humid climate, stack ventilation is inefficient due to small temperature difference between the inside and outside of naturally ventilated buildings. Hence, the solar induced ventilation by solar chimneys is a feasible alternative in enhancing the stack ventilation [29].

In practical projects, solar chimneys can be integrated into either walls or roofs, forming the two main configurations including both wall solar collector (solar wall or Trombe wall) and roof solar collector. For one thing, they are used in the buildings without air-conditioning systems to improve indoor thermal environment by natural ventilation. For another, they are also adopted in the buildings with air-conditioning systems. Under these circumstances, solar chimneys can be used to reduce the accumulated heat of the house continuously. Khedari et al. [40] reported that the solar chimney house in a hot climate consumed, depending on operating condition, 10–20% less electrical power compared with the common house. With the air-conditioning system turned on in the afternoon, the air-conditioning system in the solar chimney house carried a lower heat load than that of the common house, by about 30%. Anyway, solar chimney technology has been regarded as an effective and economical design method in low carbon buildings.

However, with only a solar chimney system, there seems to be little potential in inducing sufficient natural ventilation to satisfy indoor thermal comfort. Generally, one or more solar chimney configurations can be implemented within a design for the purpose of increasing the air movement through a building and thus potentially increasing the thermal benefits of natural ventilation.

In order to achieve a desired natural cooling effect, it is interesting to combine the solar chimneys with natural cooling systems including evaporative cooling, underground cooling, solar cooling, etc. The pre-cooling of external air before entering the building can thus be achieved by natural means. Such design approaches are suggested to be meaningful especially when the outdoor air temperature exceeds the thermal comfort limit. However, the existing reports are mainly based upon theoretical investigations. More experiments are still needed to be done so as to testify the performance of the integrated systems. Besides, it seems necessary to carry out further researches including both the optimization and control strategy of such integrated systems in different climates to provide more instructions for the practical engineering designs.

The natural ventilation performance of solar chimneys can also be enhanced by active solar systems comprising both solar cells and solar collectors. As a simple method, solar chimneys can be designed to work in conjunction with a fan powered by solar cells to enhance the flow intensity when required. Such integrated approach has the advantage of simplicity. Moreover, it seems to be a feasible way to promote the use of photovoltaic panels. Although the total radiation-to-exergy efficiency by using solar cells to induce ventilation is higher than that by solar collectors [38], it is still meaningful to use solar collectors to enhance natural ventilation performance of solar chimneys in some projects. With regard to large-scale solar collector systems, there is usually too much superfluous heat in summer and transition seasons. In this case, the superfluous heat of solar collectors may be used for the enhancement of natural ventilation on condition that solar chimneys are reasonably designed in the buildings.

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